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HIGH-SENSITIVITY BROAD-FREQUENCY-RESPONSE FIBER-OPTIC RADIO-FREQUENCY (RF) FIELD SENSOR

Richard S. Smith and Laszlo Koves

Mission Research Corporation

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13. ABSTRACT *(Maximum 200 words)*
Mission Research Corporation has developed a minimally-perturbing, broadband, fiber-optic RF probe for AFRL, Rome. This probe operates from 100 MHz to 18 GHz as limited by an output low-noise amplifier. Without its output amplifier, its response is flat from below 1 MHz to 8 GHz, but drops considerably from 8 GHz to 18 GHz. The probe outputs an RF signal proportional to the RF field at the probe head. This frequency response along with dipole-like antenna patters at 2, 8, and 15 GHz were measured at AFRL, Rome, NY. The output RF voltage is approximately 10 -4 meters times the field (below 8 GHz). The noise-equivalent RF field level is tenths of mV/m times the square root of the noise bandwidth of the read-out device (e.g., the resolution bandwidth of a read-out spectrum analyzer). Advantages of the probe include very low perturbation of the fields being measured, a single fiber to the probe head (separate input and output fibers are not needed), and control of sensitivity stability from the data-room end of the fiber.

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1. INTRODUCTION

The work reported here was in support of a customer mission to measure or monitor the electromagnetic (EM) environment aboard aircraft. It is Mission Research Corporation's understanding that the purpose of this measuring/monitoring capability was as a tool in identifying EM-related causes of failures or other problems with airborne systems. In addition to the Broad Agency Announcement (BAA) contract awarded, a Phase-I SBIR program to consider the processing/recording system was awarded (Contract No. F30602-97-C-0160), but (due to changing mission at AFRL/IF) there was insufficient support for the EM environmental sensing and recording mission for it to proceed to Phase II.

Thus, the probe development work reported here was scoped to build, optimize, demonstrate, and deliver a probe the design of which was almost completely generated under separate funding [1]. The stated objective of this work was "to identify specific Rome Laboratory RF-sensor requirements and to develop and deliver to Rome Laboratory a fiber-optic radio frequency (RF) sensor which responds to radiated RF fields, which is optimized, in so far as is possible within the scope of the contract, for Rome Laboratory purposes." Note that, as a cost-cutting move, the program was proposed with no dedicated laser to be delivered with the probe system—the work was performed using a laser system already existing at Mission Research Corporation (MRC).

The first task of the program was to determine complete requirements for the probe system. This was somewhat difficult due to the changing priorities and missions. However, some requirements provided by Rome personnel included that the probe must be a fiber-optic probe, that it must operate from 300-MHz to 18-GHz, and that it must "measure 0.1 V/m."

This later specification was of limited use, since no noise bandwidth or signal-to-noise ratio was specified. For example, to be able to measure 0.1 V/m in a 1 Hz bandwidth with a 3-dB signal-to-noise ratio would require that the noise equivalent radiated electric field be an easily-achieved, not-very-sensitive 50 mV/m per root Hz [2]. On the other hand, to be able to measure this in a 1-GHz noise bandwidth with a 40 dB signal-to-noise ratio would require a very-difficult-to-achieve, extreme-sensitivity, noise equivalent radiated electric field of about 30 nV/m per root Hz.

MRC decided to develop a probe sensitive enough to measure any field greater than that to which all military aircraft are supposed to be protected from, as specified by Military Standard 461. The reasoning here is that fields smaller than this would be of little interest, since military systems must be hardened to all such smaller fields according to the standard. This standard states that systems must be hardened to fields below 20 V/m from 100 MHz to 1 GHz and 50 V/m from 1 GHz to 18 GHz. Although no bandwidth is given, a quick survey of available EM sources indicated that most have modulation bandwidths of 100 MHz or less (pulse lengths of 10 ns or greater). Thus, 100 MHz was chosen as a maximum noise bandwidth for these field levels. This requires that the noise-equivalent field of the probe must be well under 2 mV/m per root Hz from 100 MHz to 1 GHz and well below 5 mV/m per root Hz from 1 GHz to 18 GHz. Other stated requirements were a 60-to-90-dB dynamic range (no bandwidth was specified, and no statement of whether this is the spurious free or the compression dynamic range); spatial response "hemispheric with minimal perturbation of measured field;" less than 0.5 W of electrical power required in the probe head; and dimensions "4 cubic inches max, not to exceed 1 inch in height."

2. PROBE THEORY AND DESIGN

Under other efforts, MRC has developed several fiber-optic RF probes using a variety of design theory and principles, and, under both previous and simultaneous programs, had generated still other probe designs [1,3-5], each design having both advantages and disadvantages depending upon the application. For the effort reported here, a design using a small, sensitive, high-impedance optical phase modulator in the probe head, driven by a small antenna, together with a fiber-optic interferometer and microwave-speed optical detector for converting the optical phase modulations into RF signals was selected. The advantages of this approach are summarized in Table 1.

Table 1. Advantages of the probe design chosen.

- Minimally-perturbing
  - High-impedance capacitive antenna load (low antenna current means low re-radiation)
  - Minimum amount of lithium-niobate (high-dielectric constant material is as perturbing as metal)
  - All dielectric fiber signal lines
  - No electronics in probe head
- Single fiber
  - Fiber comes out of single end of probe head
  - Easy to place in tight spaces
- Stability control from interface box (sensitivity of competing lithium-niobate, optical-waveguide, Mach-Zehnder AM modulators varies with temperature unless electronically stabilized)
- Inexpensive fiber-coupling method

Figure 1 schematically illustrates this probe system design, and Figure 2 illustrates the design of the probe head. The heart of the system is the Michelson-type fiber interferometer, consisting of the fiber splitter, the four fibers coming out of it, and the two reflectors—the reflector in the probe head (see Figure 2) and the mirror. Light from the laser is split into approximately equal amounts to the probe head and to the mirror. The return light is recombined in the splitter, with about half going back to the laser, where an optical isolator absorbs it, and about half going to the microwave-speed photodiode (photodetector). Thus, when the probe

head generates RF/microwave phase modulations of the light in that leg of the interferometer in response an RF/microwave electric field picked up by the probe-head antenna, the extent to which that light constructively or destructively interferes with the light from the mirror is correspondingly varied at this same RF/microwave. This results in an RF signal out of the high-speed optical detector (which responds to optical power). The output signal is coherent with the RF field being measured—phase as well as amplitude can be measured.

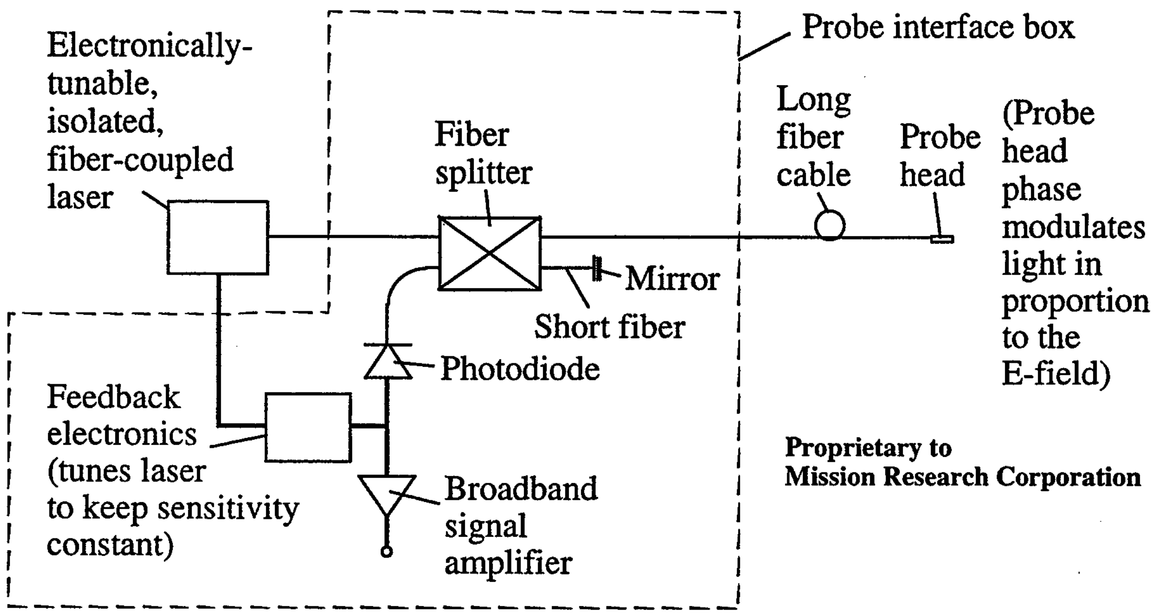

Figure 1. Probe system schematic.

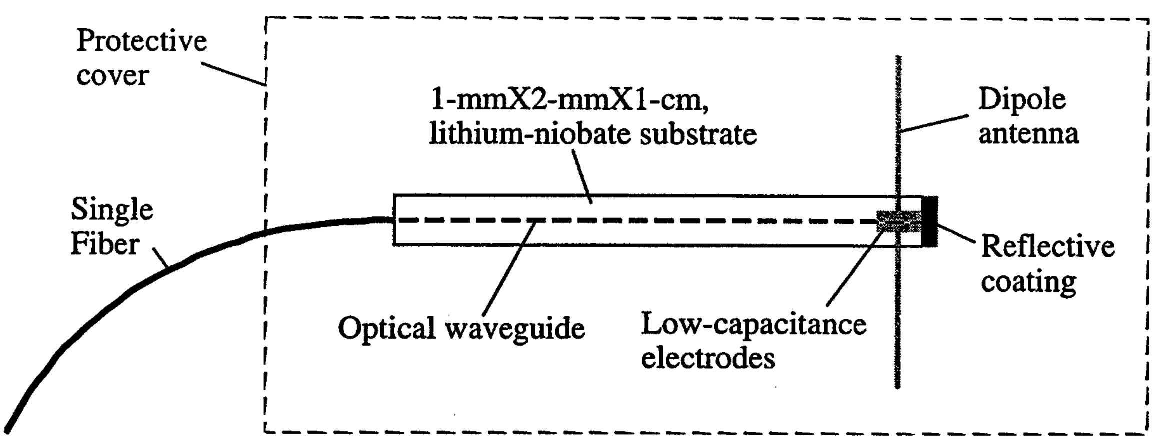

Figure 2. Probe head design.

The leg of the interferometer going to the probe head is much longer (by about 19 m) than that going to the mirror. Because of this, if the wavelength of the light is changed, the relative phase of the light wave from the probe head changes relative to that of the light wave from the mirror. Thus, this relative phase can be controlled by tuning the laser. The laser used is electronically tunable, and the feedback electronics are used to tune the laser to keep this relative phase constant at the point of maximum sensitivity to the small, RF/microwave phase modulations generated in the probe head. (This is the so-called "quadrature" point, or the point where the average phase between the two light waves is 90°.) The laser used (existing at MRC prior to the contract) was a Lightwave Electronics 126-1319-350, semiconductor-laser-pumped, Nd:YAG laser, tuned by a piezoelectric crystal which squeezes the crystal laser cavity.

Not shown in Figure 1 are a number of fiber connectors, which are responsible for considerable optical power loss. About half of the light to the probe head is also lost, primarily in the process of coupling into and back out of the lithium-niobate waveguide. A second optical isolator, also not shown in Figure 1, was also placed between the splitter and the detector. The microwave amplifier was a Miteq Model AFS4-00101800-40-ULN, 0.1-to-18-GHz, low noise amplifier, which has about 25 dB gain and a noise figure of about 4 dB. Without this amplifier, the probe frequency response extends down well below 1 MHz (down to the upper edge of the feedback-electronics bandwidth).

The probe head (Figure 2) consists of a minimum-size, lithium-niobate chip with a single optical waveguide and a reflective coating on the end opposite the interface to the fiber. A short pair of electrodes on either side of the waveguide at the reflective-coating end converts the voltage applied by the antenna (in response to the radiated electric fields being probed) into stronger electric field inside the lithium niobate of the waveguide. The fiber coupling was done using a relatively inexpensive method proprietary to our subcontractor, Integrated Optical Circuit Consultants of Cupertino, CA. The reflector coating is a hard, multi-layer, dielectric coating, which is (according to the coater) more than 99% reflective.

As lithium niobate has a very high dielectric constant, without the antenna and electrodes the field in the material would be a small fraction of that in free space, and the sensitivity would be very poor. On the other hand, because the electrodes are configured for very low capacitance (around 0.05 pF), little current is drawn by the antenna, and the perturbation is minimal. (This perturbation can be looked upon as re-radiation by the antenna, which is proportional to the square of the current times the radiation resistance of the dipole. Because of the high impedance of the chip, the current is very small, and because the antenna is short—about 8-mm long—the

radiation resistance is very low at all but the highest frequencies.) It is important to use the absolute minimum amount of lithium niobate (as we did), however, because, with dielectric constants of 26 in one direction and 43 in another, lithium niobate is as perturbing as metal.

3. PROBE DEVELOPMENT

The pre-existing probe design was reviewed early in the program, and fabrication or purchase of components began almost immediately. When the components were completed or received, they were tested. The probe system was then constructed, first demonstrated in MRC's lab for MRC personnel in February of 1998, and packaged in essentially its final form in April of that year. Figures 3 and 4 are photographs of the probe head and the probe interface box (taken shortly after the initial construction and packaging). Some more recent photographs are shown in Section 4 and in the Appendix.

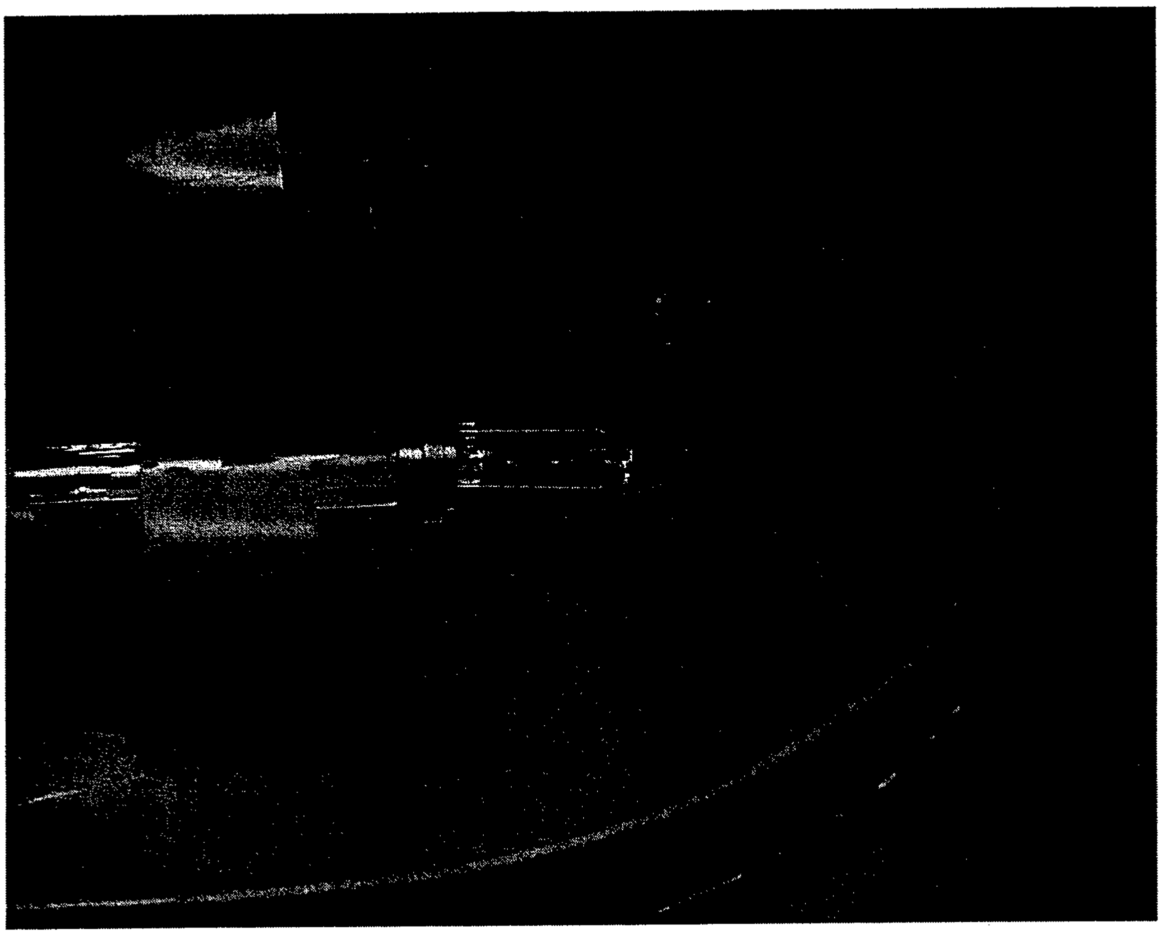

Figure 3. The probe head. The probe antenna and modulator, supported by thin, glass structural members, are in the center. A small, acrylic tube (center left) supports this assembly and contains the fiber, the jacket of which can be seen inside the tube at the far left. An acrylic flange for supporting one of the spherical, ping-pong-ball, protective covers, seen at the top, is on the end of the tube nearest the antenna/modulator assembly. The probe is shown resting in a storage/shipping box, held down by tape and protected by a semi-circular strip of cardboard.

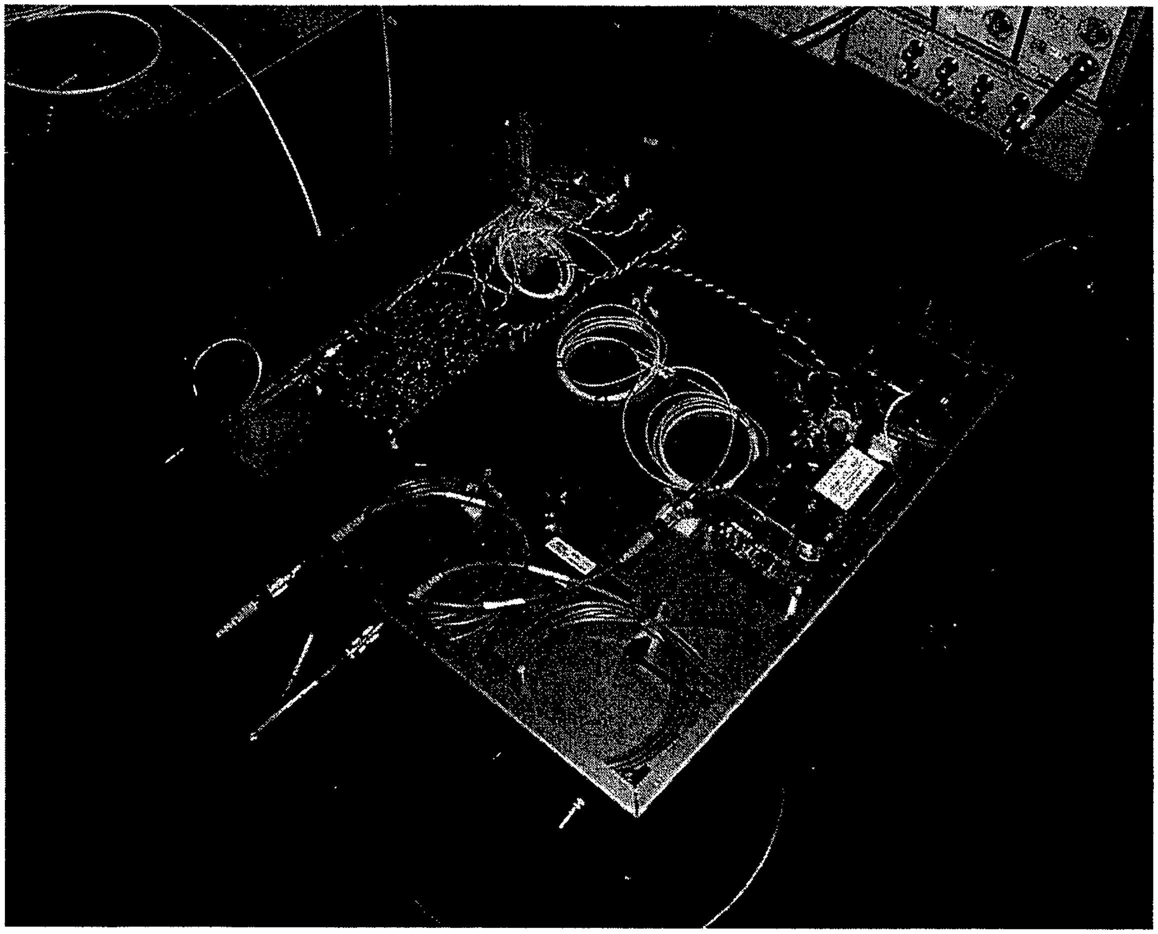

Figure 4. The probe interface box, containing the Wave-Optics fiber splitter (bottom corner of box), a power supply (right corner), detector and feedback electronics (upper left portion of box), and the optical isolator not shown in Figure 1 (between the power supply and feedback electronics). The laser (not supplied under the contract) and the probe head are not shown, but fibers coming from/going to them are seen connected to the box through the lower right bulkhead. (The Miteq amplifier is not shown, and various test leads are connected.)

While off-site demonstration and delivery could have been performed at that time, a sensitivity drift of over ± 1 dB was observed, and work to eliminate this drift continued for many months. In addition, several components were seen to not meet specifications, and considerable work to remedy this problem was performed as well. The input isolator, for example, had too-high insertion loss, along with a cross-polarized connector, and was sent back to the manufacturer for repair or replacement; the system photodetector was delivered with a sub-spec frequency response, and a replacement was requested; reflections in the fiber coupler were above spec (or, equivalently, the directivity was too low); and some other fiber components were seen

to have inadequate polarization extinction ratios. The reflection and polarization problems contributed to the sensitivity drifting.

Our first attempt to reduce this drifting was to improve the polarization extinction ratios of various components. A new laser-to-fiber coupler and a polarizing fiber (which attenuates the cross-polarization component) were received, installed, and tested. This had only a minimal effect on the drift. It was then determined that out-of spec return optical power from the fiber splitter was observed. This combined with the reflections from the probe head and mirror causes an optical cavity to be set up ("etaloning"). This problem induces drifts since the additional reflected power adds either constructively or destructively depending on the optical phase, which varies 180° when the fiber length changes by less than half a micrometer due, for example, to thermal expansion/contraction or to vibrations (etaloning).

To conclusively demonstrate that most of the drift was due to the splitter (made by Wave Optics of Mountain View, CA), a different splitter, from a different manufacturer (Canadian Instrumentation Research of Ontario, Canada), already existing at MRC was substituted into the probe system. When this was done, most of the drifting went away. Figure 5 shows part of a strip chart recording of the RF output of the probe system (without the Miteq amplifier) over time with the probe head immersed in a constant RF field. The time scale for this four-hour test is 50/minutes per large division and the scale is arbitrary but linear. Both short-term drift (infrequent, relatively rapid fluctuations seen in the strip-chart record) and long-term drift (many seconds to many minutes) are present. Most of the short-term drift was apparently due to variations in RF pick-up. Because at the time of this test, the probe system power supply had burned out and had not yet been replaced, an external power supply was used, and the probe electronics enclosure could not be closed, allowing noticeable RF pick-up by the detection electronics. The short-term fluctuations were observed when a person walked near the system. The long-term drift is within about $\pm$ 0.1 large division around approximately 2.7 large divisions.

The Wave Optics splitter was sent back to the manufacturer, who found and corrected reflection problems with the fiber connectors. However, when it was returned, it still caused substantially more drift than were observed with the substitute, Canadian Research splitter. Near the end of the program it was seen that many things can cause small reflection or polarization problems in the various polarization-maintaining fiber-optic components (e.g., the tightening of screws attaching bulkhead-feedthrough fiber connectors to a bulkhead).

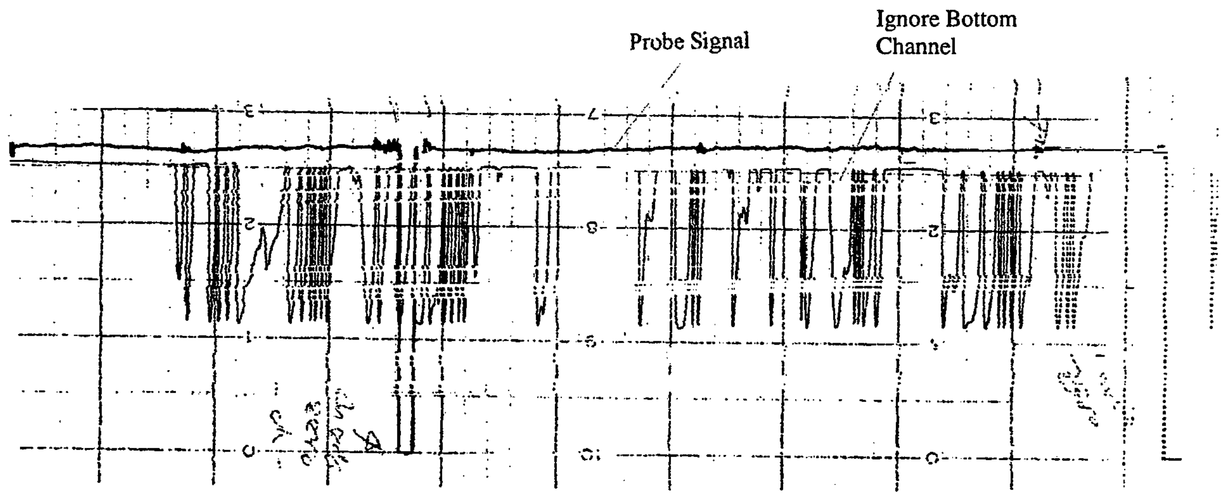

Figure 5. **Strip chart recording of probe drift. The vertical scale is arbitrary but linear, and the horizontal scale is 50 minutes per (large) division.**

The Miteq amplifier was also seen to cause substantial thermal drifts, as it warmed up. When only a small, manufacturer-recommended heat sink was used, gain drifts of around 2 dB were observed as the amplifier heated up to above 60° C. The amplifier was not built using temperature compensation techniques, but according to Miteq, it can be substantially temperature compensated for only a small additional cost. Later the amplifier was mechanically mounted directly to the probe interface box.

4. PROBE TESTING

In January of 1999, the probe system was taken to AFRL, Rome for testing and demonstration for AFRL personnel. This testing was originally scheduled for December, 1998, but the probe was broken during November of that year, and repairs took several weeks. Because of the probe's breaking, MRC undertook to improve the protective jacket, ending up replacing both the acrylic flange and ping-pong-ball-type, spherical protective jackets with a thin-walled, polycarbonate tube surrounded by a layer of 1/2-inch-thick foam rubber. Figures 6 and 7 show the probe head in the new protective jacket. The protective polycarbonate tube is supported from the back (the fiber entry/exit end) by an acrylic plate with holes to minimize RF perturbations. These holes can be seen in Figure 7. For added protection, a mylar sheet, also having many holes, covers the other end. The polycarbonate tube, which is shielded from view in the photographs by the foam, also has many holes to minimize RF perturbations.

The probe system was packed in cardboard cartons using various padding materials. It was then successfully transported to Rome (using an overnight delivery service). The only problem seen in setting up the probe system for test was the laser, whose fiber coupling had been knocked out of alignment during shipment. The laser (pre-existing at MRC and not part of the deliverable probe system) was externally fiber coupled using optical translation and tilt stages on a small breadboard by MRC. The principal investigator was able to realign the laser in less than a half hour, after which the probe system was ready for use.

Figure 8 shows the probe head on a wooden arm on a motorized, rotating arbor head at the top of a mast in the anechoic chamber at Rome (being attended to by the PI on a trapeze). The arbor head allows rotation about a horizontal axis for purposes of determining antenna patterns. The base of the mast to which the arbor head is attached allows rotation of the probe about the vertical axis. Because the arbor head is metal, the probe was attached to the arbor head using an approximately two-foot-long strip of plywood (see Figure 8) to provide some separation from the RF-scattering, metal arbor head. The probe interface box in the data room at Rome is shown in Figure 9. The RF output of the probe interface box is connected via coaxial cable to an HP 8496B spectrum analyzer, used for measuring the probe signals during the Rome tests.

Testing at Rome consisted of investigating the frequency response of the probe from 1 to 18 GHz and the measurement of antenna patterns at three different frequencies. Frequency response measurements were made manually—every half GHz. An Electro-Mechanics Inc.

Model 3115 (S/N 2539) broadband horn radiator was used in all the testing. For purposes of field calibrations, Rome personnel used an HP 8510 network analyzer to measure the RF losses in the cables and the coupling coefficient of a directional coupler used to monitor the power to the radiating horn. The coupled power was fed into the same spectrum analyzer used to measure the probe system output power.

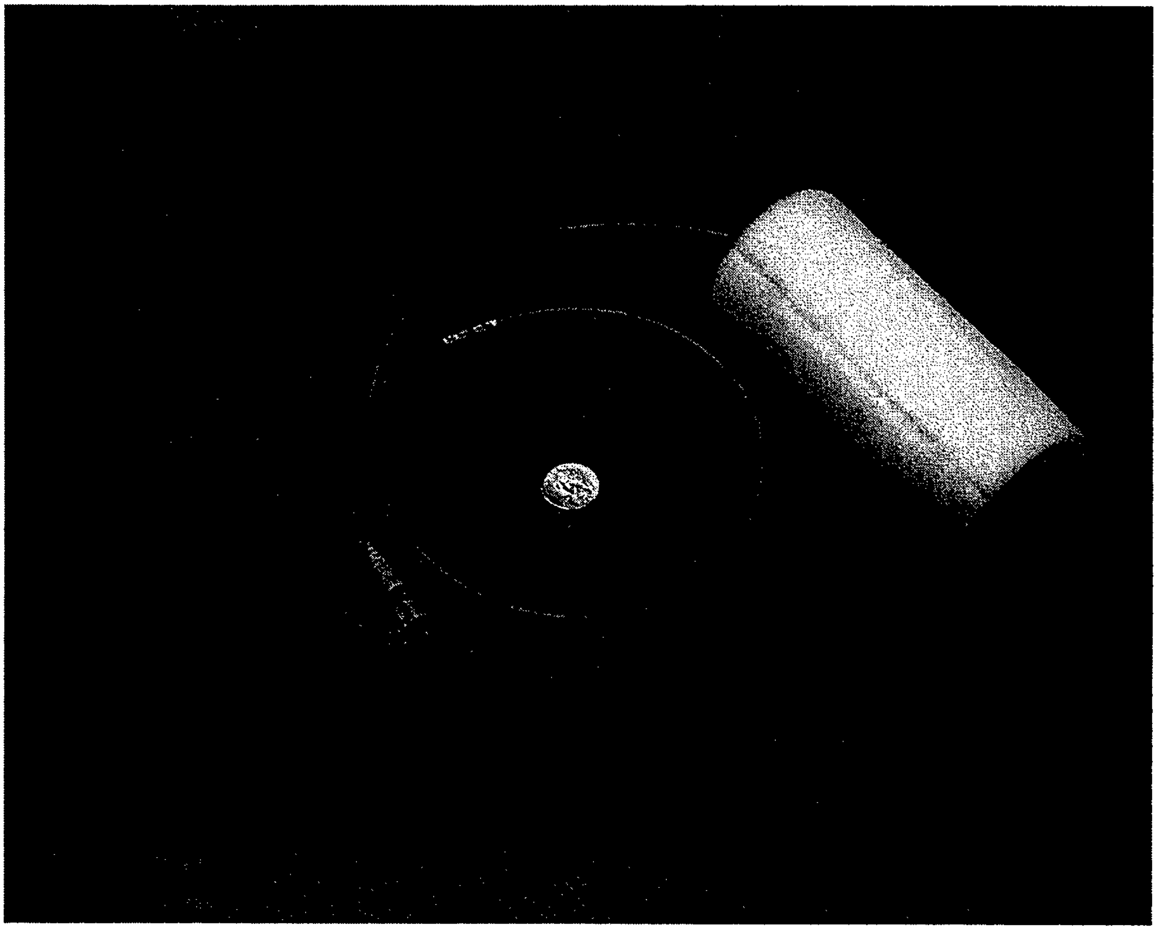

Figure 6. The probe head in its latest, foam-rubber-covered protective jacket. A sheet of mylar with holes punched in it is cemented across the end for further protection. A coin (quarter) is also shown to indicate scale.

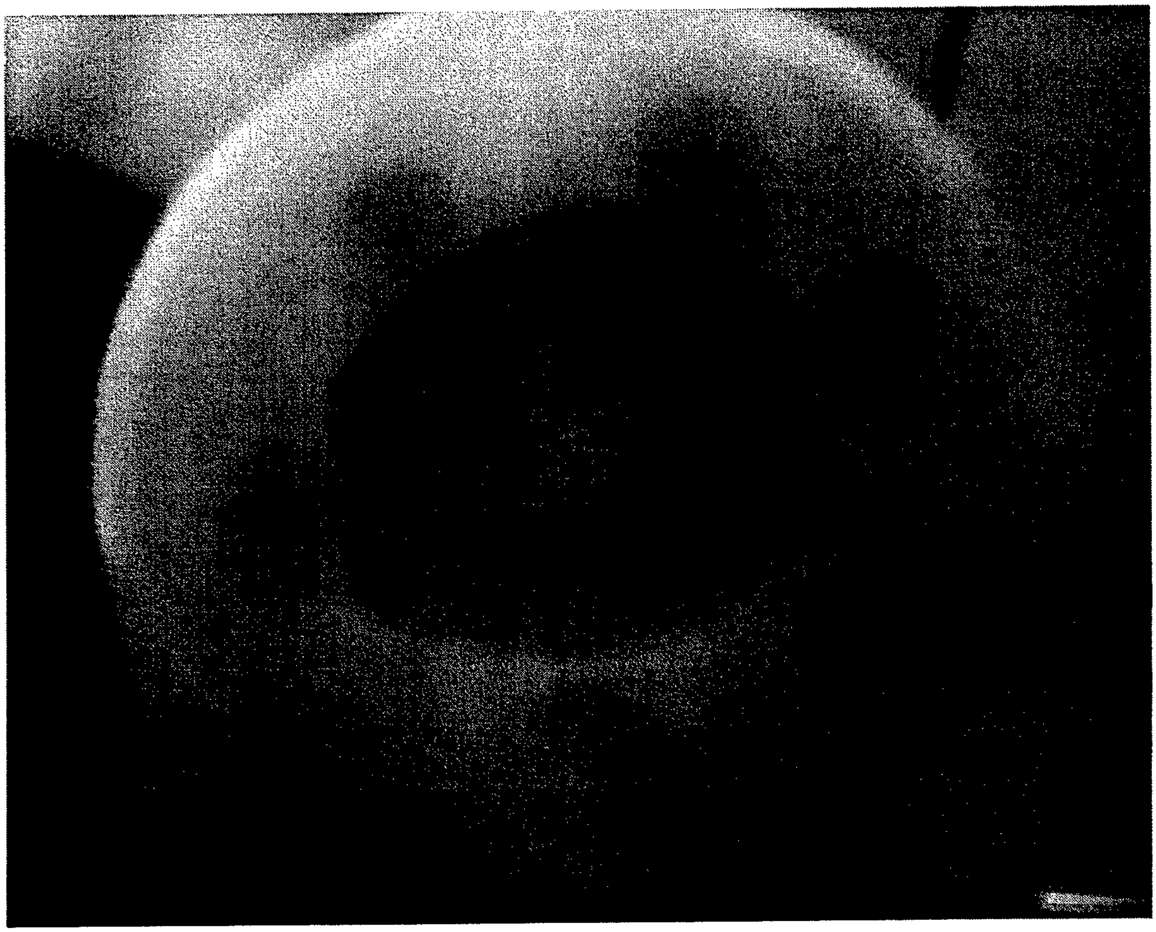

Figure 7. Close-up, end-on view of the probe head in its latest, foam-rubber-covered protective jacket.

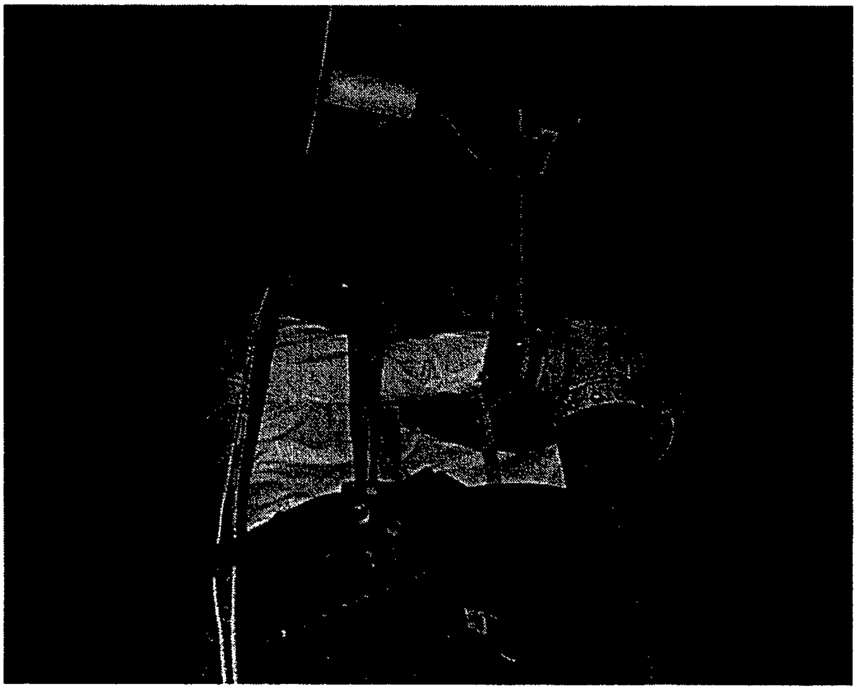

Figure 8. The probe head on a wooden arm attached to a rotating arbor head at the top of a mast in the anechoic chamber at Rome (being attended to by the PI on a maintenance trapeze).

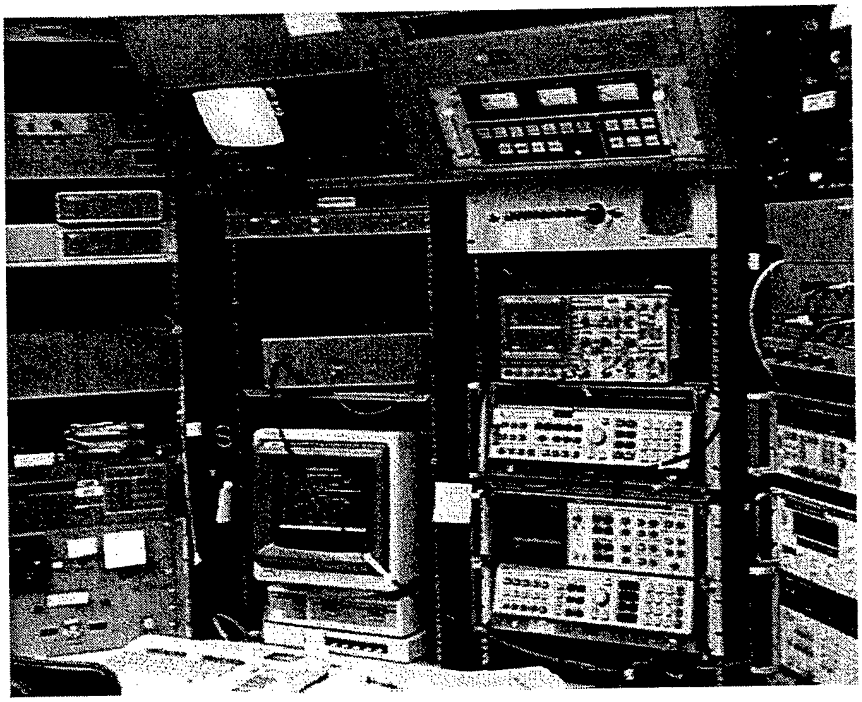

Figure 9. The probe interface box in the data room at Rome (just to the left of center, above the computer). The probe RF output is connected to the HP spectrum analyzer used in the testing.

The spectrum analyzer's linearity was verified to be within about a tenth of a dB over the range used by calibrating an attenuator (using the HP8510) and measuring the power with the spectrum analyzer with and without the attenuator in line. Manufacturer-supplied gain curves for the horn were used to convert RF antenna power into RF field at the probe. Note that the Miteq amplifier stopped functioning part way through the testing and was removed (for much of the low-frequency data, which was obtained last). All data presented below, however, is for the probe system with the output amplifier present—the manufacturer-supplied amplifier gain values were added to the measured output power for cases where the amplifier was removed.

The frequency response data was obtained and processed to correct for attenuation and coupling factors. Because the probe system output is an RF voltage proportional to the radiated E-field at the probe, one method of specifying the probe response is to give this proportionality constant, which has the dimensions of length (voltage = E-field X length). We call this

proportionality constant, l_{aeff}, the "actual effective length" of the probe (as opposed to the quantity "effective length" used in antenna text books which relates the E-field to the source voltage in an antenna's equivalent series circuit). Moreover, because the output impedance of the probe system is 50 Ω, the probe system can be viewed as a 50-Ω-output antenna, and, in this context, the usual antenna quantities of effective aperture and gain apply. The effective aperture, A_{eff}, is given by $A_{eff} = P/\Gamma$, where P is the RF power out of the probe system (in watts), and Γ, is the radiated RF power flux (W/m^2) at the probe. (The power flux is related to the E-field by $E_{rms} = (377\Omega \bullet \Gamma)^{1/2}$.) The gain, G, is then given by $G = 10 \log(4\pi A_{eff}/\lambda^2)$.

Figures 10, 11, and 12 show the gain, actual effective length, and effective aperture of the probe, respectively. The most useful quantities are probably the actual effective length and effective aperture. To obtain the E-field at the probe from the measurement output RF voltage, divide by the actual effective length. To obtain the power flux (Γ in W/m^2) at the probe from a probe output signal (in W), divide by the effective aperture. Note that the absolute values of these numbers are dependent upon the amount of laser power through the system, which will change if different coupling efficiency is achieved or if a different laser is used.

The dependence of the probe response on frequency seen in Figures 10-12 is not well understood at this time. The response is expected to be flat at low frequencies, since the capacitive source impedance of the dipole antenna at low frequencies forms a frequency-independent capacitive voltage divider with the capacitive optical phase modulator to which the dipole antenna is connected. Fairly flat response is indeed seen up to about 8 GHz. The antenna inductance becomes important as the antenna length becomes comparable to the RF wavelength, and a resonance between this inductance and the series combination of antenna and modulator capacitance is expected. Beyond 8 GHz, the response drops rapidly until about 9 GHz. It flattens again out up to about 14.5 GHz, where it again rapidly drops. Rapid changes in the response curve could be resonance related. The existence of two rapid changes in the response curve suggests greater complication than a simple LC resonance between fixed antenna inductance and fixed antenna-plus-modulator capacitance. (The dipole dimensions are less than one wavelength at the frequency of the second rapid change in the response, so the presence of a second dipole resonance is unlikely.) The various parts of the dielectric-tube, acrylic-support, foam-rubber protective probe head jacket are other potential causes of the complications in the frequency response. Resistance in the probe head circuit is used to flatten out such resonances. Since it is not known how much resistance is in the circuit, it is possible that the resistance is excessive, partially accounting for the reduced response at high frequencies.

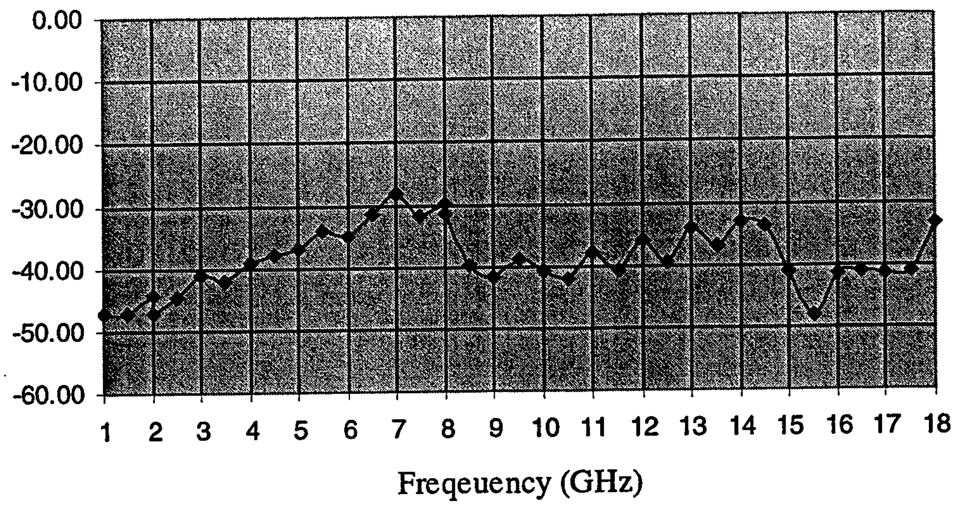

Figure 10. Probe "Gain" vs. frequency.

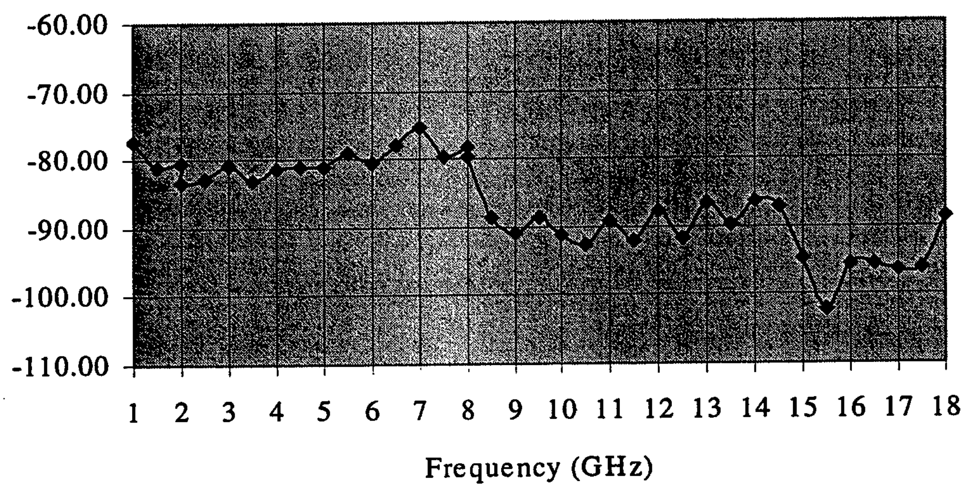

Figure 11. Probe "actual effective length" (dB - m). Divide this into the probe output signal RF voltage to obtain the radiated RF electric field (V/m) at the probe.

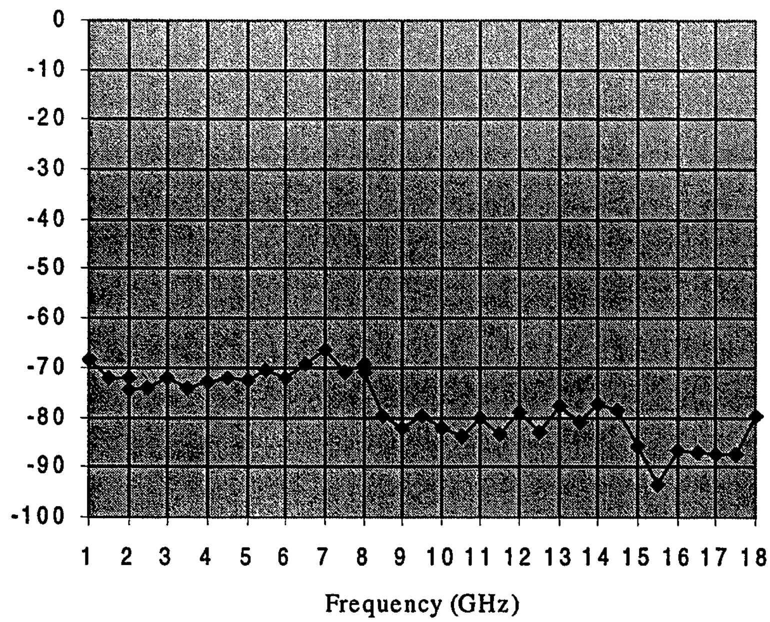

Figure 12. Probe effective aperture (dB - m^2). Divide this into the probe output signal RF power to obtain the radiated RF power flux (W/m^2) at the probe.

In order to estimate the minimum field that can be measured, or, more precisely, the noise-equivalent RF field of the probe system, an output noise measurement is needed. Such a measurement was made at MRC just before shipping the probe system to Rome, using the internal noise-measurement function of MRC's HP 8593A spectrum analyzer. At 10 GHz, the noise measured by the spectrum analyzer was -137.7 dBm/Hz. Since the analyzer noise alone was measured to be -140.0 dBm/Hz, the actual probe system output noise was -141.6 dBm, equivalent to an RF output voltage of $1.86 \bullet 10^{-8}$ V rms. (Noise power is additive.) Since the "actual effective length" of the probe (defined as the voltage out of the probe system divided by the electric field at the probe head) at 10 GHz is $2.82 \bullet 10^{-5}$ m (≈-91 dB-meter in Figure 11), the noise-equivalent field at 10 GHz is about 0.66 mV/m/√Hz rms, or $1.15 \bullet 10^{-9}$ W/m^2/Hz ($1.15 \bullet 10^{-10}$ mW/cm^2/Hz) noise-equivalent RF power flux [2]. The signal-to-noise ratio in a 100-MHz noise bandwidth for the Mil-Std-461, 50 V/m field would be 17.5 dB for this case (see Section 1).

The noise was not measured at other frequencies, but, assuming the same noise level, the noise equivalent field at low frequencies (corresponding to -80 dB—meter actual effective length), is 0.19 mV/m/√Hz ($9.2 \bullet 10^{-11}$ W/m^2/Hz or $9.2 \bullet 10^{-12}$ mW/cm^2/Hz). For the Mil-Std-461, low-frequency, 20-V/m field the signal-to-noise ratio would be 20.4 dB, and for a 50 V/m field it would be 28.4 dB. At 15.5 GHz, however—the low point in the frequency response curves—the

signal to noise ratio for the pertinent 50 V/m field would only be about 6 dB. Unfortunately, due to limited testing time at Rome, we were not able to check whether or not the low recorded response at this frequency was due to a data taking or recording error. The next worst signal-to-noise ratio for a Mil-Std-461 field is approximately 12.4 dB. All of these signal-to-noise ratios are potentially suitable for the originally intended, EM-environmental-monitoring application.

We note that the signal to noise ratio can be improved simply by increasing the laser power. The improvement in dB would be ten times the log of the increase in optical power. A similar, already-isolated-and-fiber-coupled laser, which would input about 10 dB more power, is available from Lightwave Electronics, Inc., and the optical detector would remain linear at about 10-dB higher input power.

Attempts were also made at Rome to measure the probe antenna patterns both in planes parallel to and perpendicular to the probe head dipole antenna at three different frequencies, 2 GHz, 8 GHz, and 15 GHz. The rotational properties of the mast and arbor head on which the probe was mounted in the anechoic chamber (see Figure 8) were used for this pattern investigation. Unfortunately, the arbor head, being metal, strongly scattered the radiated RF energy, substantially effecting the measured antenna patterns. The arbor head was located about 2-ft away from the probe head. As in all of the testing performed at Rome, the radiated RF was polarized in the horizontal plane.

Figures 13 and 14 were obtained at 2 GHz. Figure 13 shows the pattern data with the probe being rotated in a vertical plane at the end of the wooden arm to which it is mount, about a horizontal axis passing through the arbor head (and parallel to the probe head dipole antenna, which was always horizontal). Patterns obtained this way are designated vertical patterns. Figure 14 shows the pattern data with the probe head rotated in a horizontal plane about a vertical axis, perpendicular to the axis of the probe head dipole antenna. Here the entire mast rotated on its base on the floor of the anechoic chamber. Patterns obtained this way are designated horizontal patterns. Figures 15 and 16 show the 8-GHz vertical and horizontal pattern data, respectively, and Figures 17 and 18, respectively, show the 15-GHz vertical and horizontal pattern data.

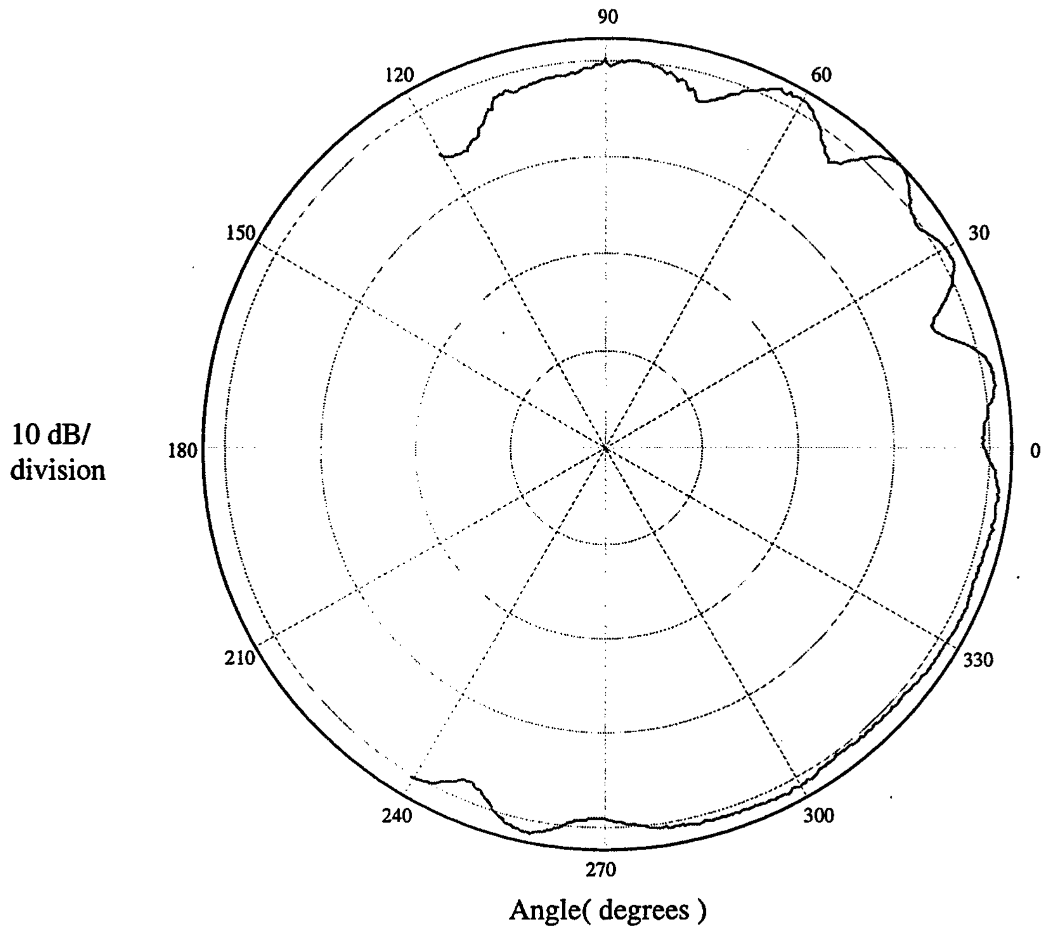

Figure 13. **"Vertical" antenna pattern at 2 GHz with probe rotated about an axis parallel to the probe-head dipole antenna axis.**

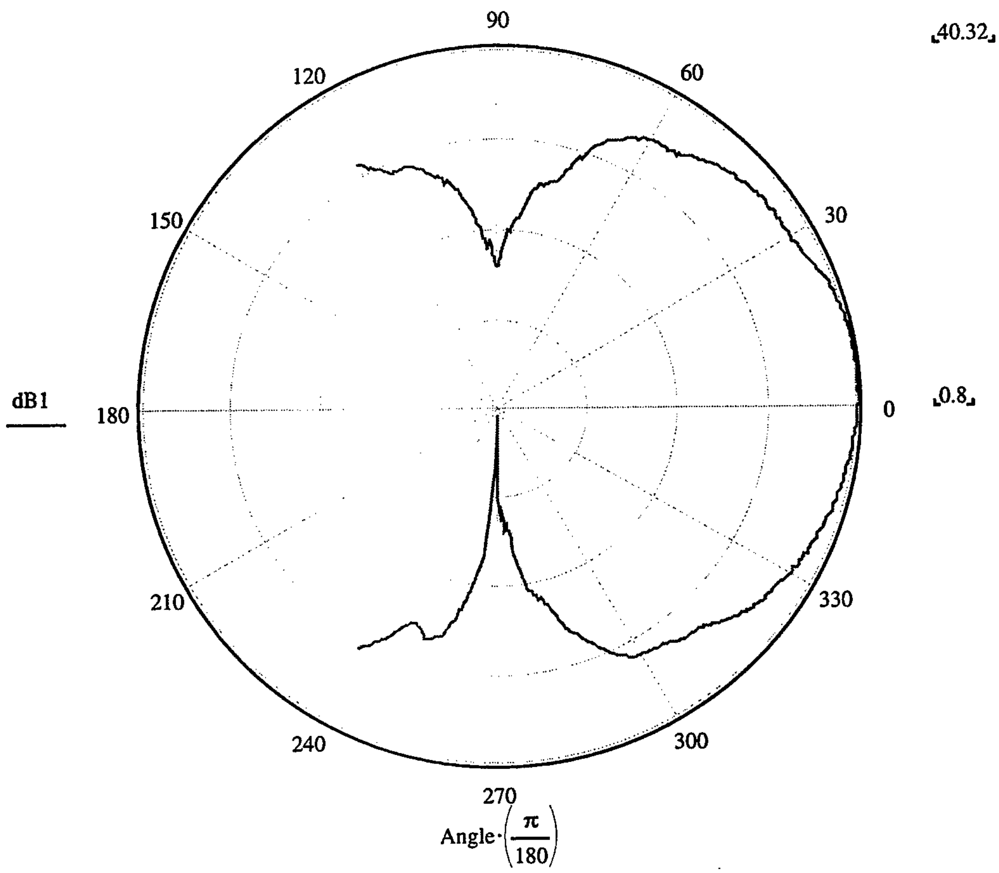

Figure 14. **"Horizontal" antenna pattern at 2 GHz with probe rotated about an axis perpendicular to the probe-head dipole antenna axis.**

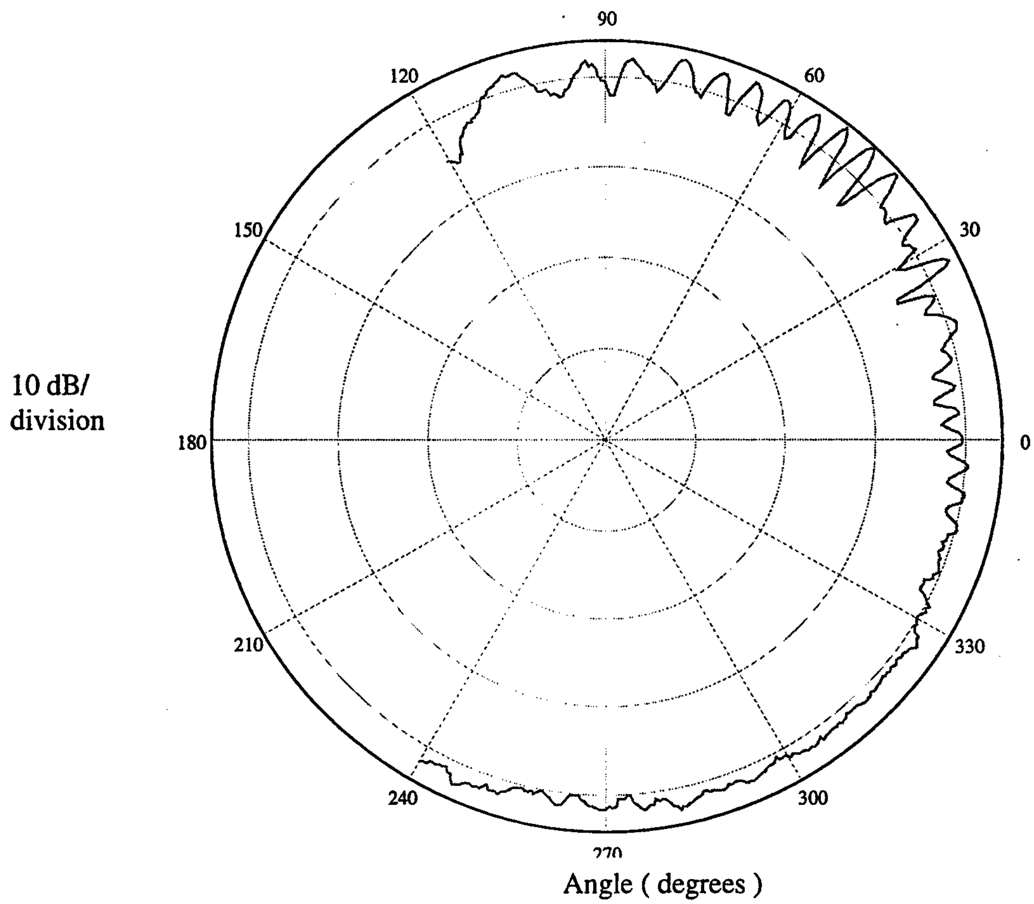

Figure 15. **"Vertical" antenna pattern at 8 GHz with probe rotated about an axis parallel to the probe-head dipole antenna axis.**

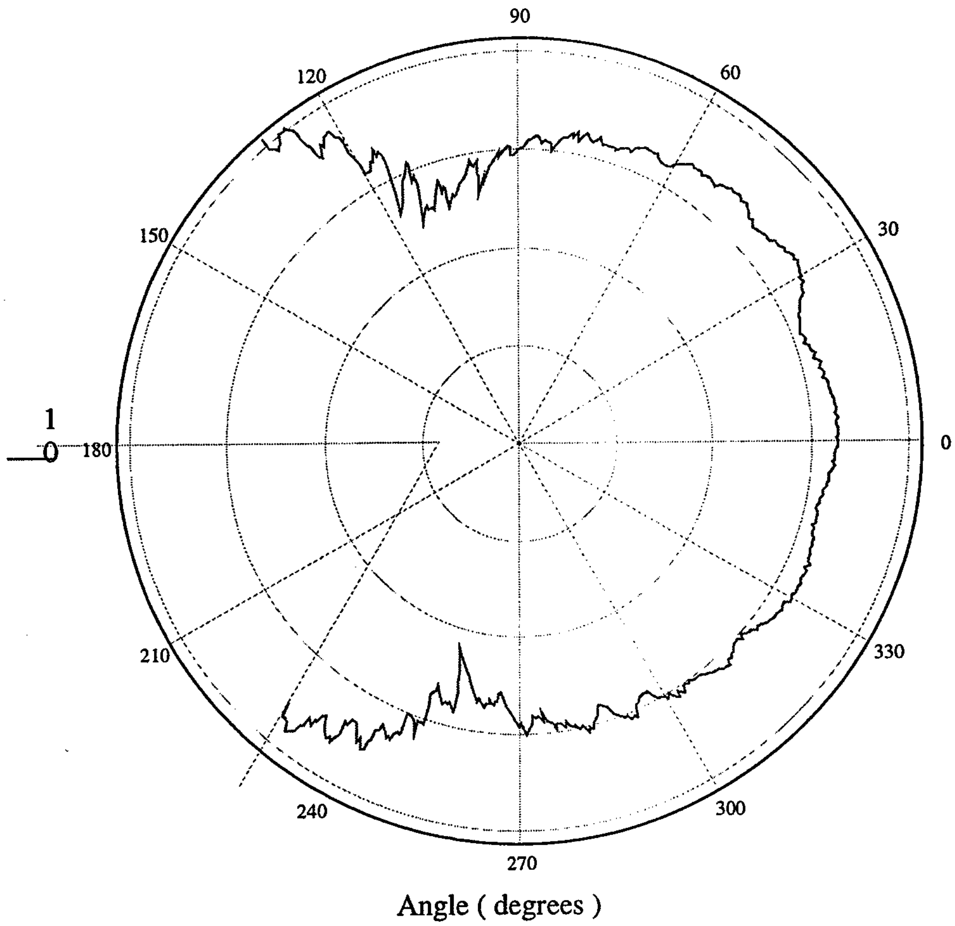

Figure 16. **"Horizontal" antenna pattern at 8 GHz with probe rotated about an axis perpendicular to the probe-head dipole antenna axis.**

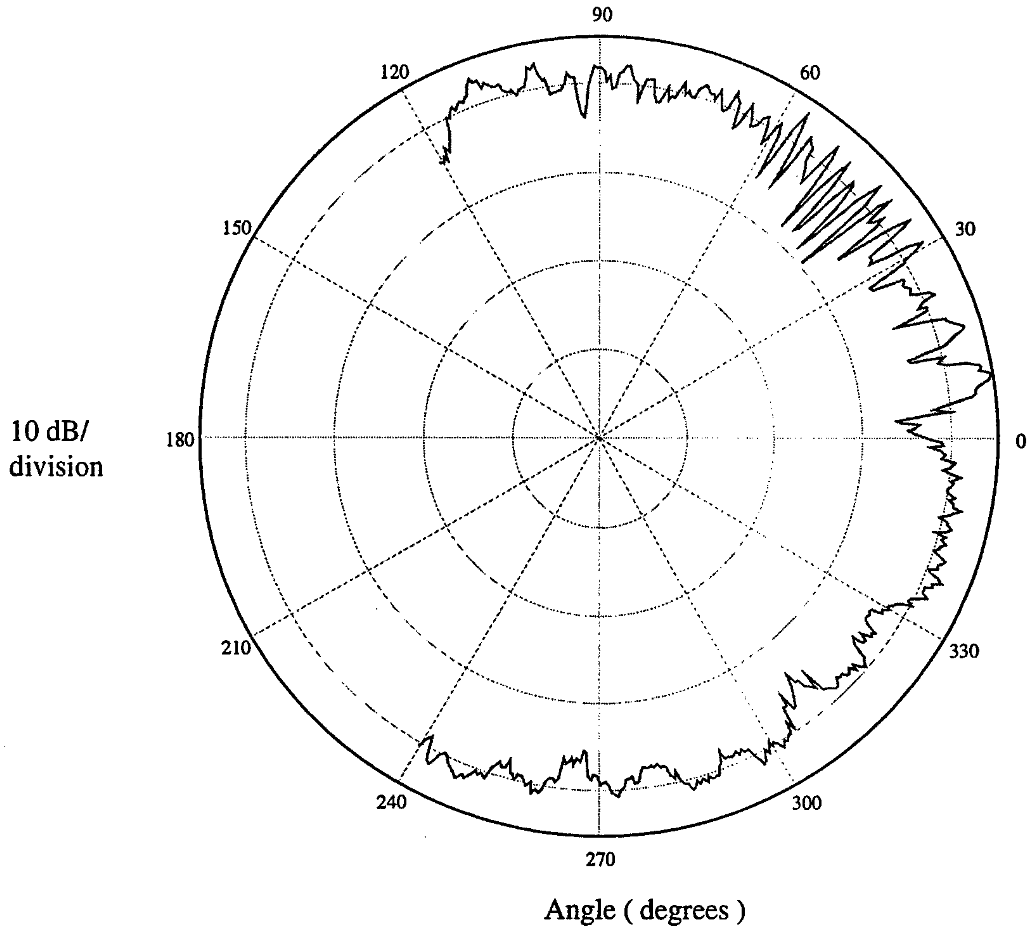

Figure 17. "Vertical" antenna pattern at 15 GHz with probe rotated about an axis parallel to the probe-head dipole antenna axis.

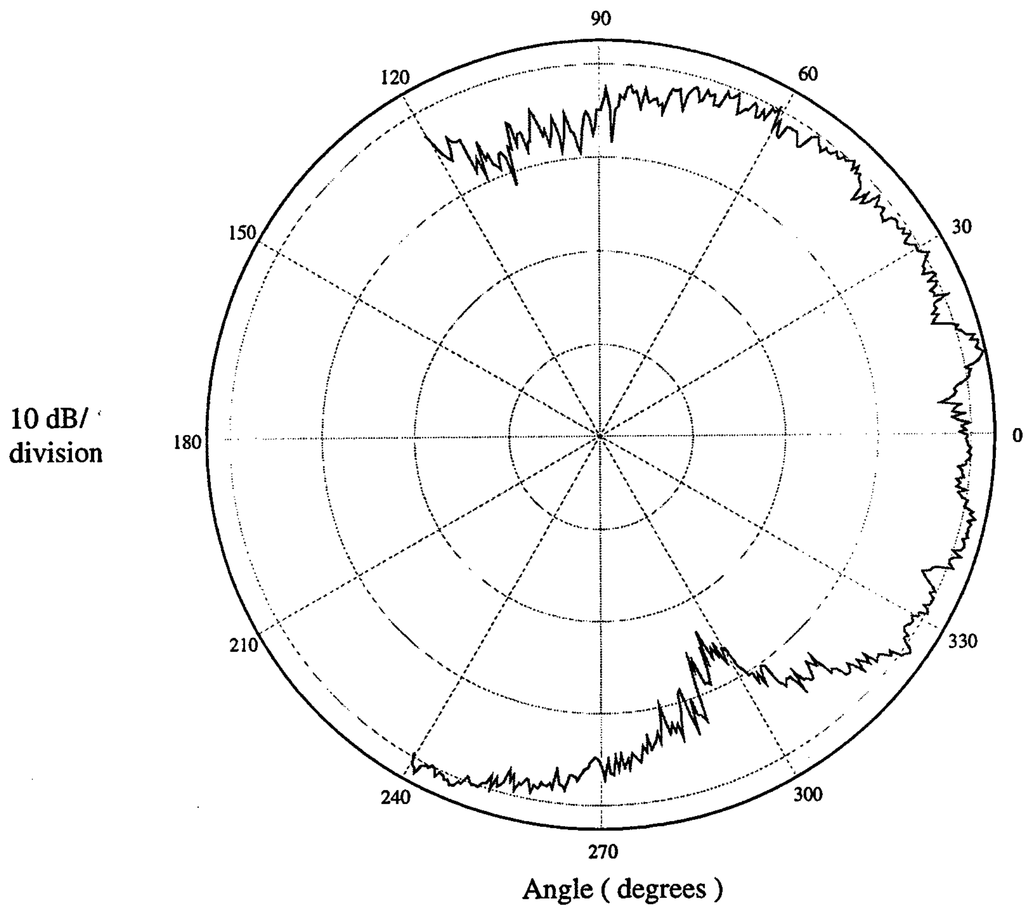

Figure 18. **"Horizontal" antenna pattern at 15 GHz with probe rotated about an axis perpendicular to the probe-head dipole antenna axis.**

Ideal vertical patterns would be perfect circles, with no variation in angle, while ideal horizontal patterns would reflect the sinusoidal dependence of the RF voltage picked up by the antenna on the angle between the radiated E-field ant the probe-head dipole antenna axis. The 2-GHz data is very much like this except for the effects of RF scattering by the metal arbor head, which is more pronounced when the probe head is rotated to a position further away from the radiator than the arbor head, occurring between roughly 0 and 180°, although some effects of scattering by the arbor head occur at nearly all angles. The higher frequency data also shows effects of field polarization rotation, most likely due to scattering off of the arbor head or off parts of the probe head itself, e.g., the protective jacket and its supporting members. (The polarization of scattered radiation can be greatly rotated from the polarization of the original radiation, since, in the plane-wave approximation, the polarization is perpendicular to the scattered direction of propagation which can be highly oblique to the original direction of propagation. Such specular scattering is most pronounced at high frequencies. At low frequencies, like 2 GHz, the radiation partially diffracts around objects as large as the arbor head.) This causes the minima in the horizontal pattern to be less pronounced and to be slightly rotated in angular position. Other than these effects which may be due to scattering off the arbor head, the antenna patterns are very much as expected for a dipole antenna.

5. CONCLUSIONS

A fiber optic RF probe system was built, tested, and demonstrated at the Air Force Research Laboratory, Rome, NY. As proposed, no laser light source is included with the deliverable probe system. All the testing was done using a laser system pre-existing at MRC.

At Rome, the probe system was shown to respond between 1 and 18 GHz, although the frequency response is not constant. Measurements at Rome, combined with a system noise measurement made at MRC's Newington, VA laboratory, indicate that signal-to-noise for RF fields exceeding those which Military Standard 461 requires military systems to be shielded to withstand is greater than 12 dB in a 100-MHz noise bandwidth. (A single measurement point exception to this, where the minimum signal-to-noise ratio is apparently about 6 dB, occurred at 15.5 GHz. The data at this point could, however, be in error. There was insufficient time available during the Rome testing to check.) These signal-to-noise ratios can all be increased by as much as 10 dB by using a commercially available, pre-fiber-coupled and -isolated laser light source instead of the pre-existing laser, fiber coupled and isolated by MRC on a breadboard. Of course, in lower noise bandwidths the signal-to-noise ratio would be much higher, e.g., a 56-to-78 dB for a 1-kHz-bandwidth receiver.

Although dynamic range has not been measured at low frequencies, the probe is expected to go into saturation at something over 10 kV/m, indicating a compression dynamic range of around 150 dB/Hz. The compression point is expected to be correspondingly higher at higher frequencies where the probe is less sensitive, so that the dynamic range is largely independent of frequency. This gives about a 70-dB compression dynamic range in the full 100-MHz noise bandwidth (meeting the 60-to-90-dB requirement). The spurious-free dynamic range can only be speculated upon, but is expected to be not much more that 100 dB + 10 log[(noise bandwidth)$^{2/3}$], or around 50 dB in a 100 MHz bandwidth. Since no electrical power is required at the probe head, the requirement of less than 0.5 W electrical power there is satisfied. Without the removable/replaceable protective cover, the probe head is an order of magnitude smaller than the required 4 cubic inches.

Antenna pattern measurements of the probe were made in planes both perpendicular to and parallel to the axis of the probe-head dipole antenna. These were very much like patterns expected for a dipole antenna—the vertical plane pattern (rotation of the probe head about an axis parallel to the probe-head dipole antenna) showing relatively little variation with angle, and

the horizontal plane pattern approaching a minimum as the probe-head dipole becomes approximately perpendicular to the E-field of the (not-scattered) radiated RF. Perturbations to the patterns have been attributed to scattering of RF energy, particularly off of the metal arbor head, used to perform rotations in the vertical plane, and located a short distance away from the probe head.

As to whether the stated requirement of "hemispheric •pa ttern] with minimal perturbation of measured field," it is not clear whether the probe patterns (with the effects of the scattering removed) can be characterized as hemispherical or not. We note that a three axis probe, having three, mutually-perpendicular dipole antennas, each with its own modulator fiber (and either separate probe-interface-box components or else fiber switches to allow sharing of these components), would allow largely isotropic, or spherical response. Such probes have been designed by MRC under separate funding, and proof of principle experiments have been conducted to partially show the feasibility of these designs [1,3-5]. As discussed in Section 2, and suggested by the pattern measurements, the probe is expected to not appreciably perturb the fields being measured, particularly where the probe can be operated without the protective jacket or the supports thereof.

Thus, essentially all probe system requirements as determined at the beginning of the program have been at least nominally met. The probe system, supplied with an appropriate laser system, is expected to be useful in measuring a single component of a free-space RF field in situations where minimal perturbations are required. Such measurements should be possible for fields from 1 MHz to above 18 GHz (0.1 GHz to 18 GHz when the Miteq amplifier is used) with the sensitivity reported above and with nominal accuracy. An operating manual has been included as an Appendix to this report.

NOTES AND REFERENCES

*1. U.S. Navy Contract No. N00421-97-C-1086 (NAWCAD, Patuxent River, MD).

2. Noise power for the most common types of high-frequency noise in an RF-Photonic system (shot noise, Johnson noise, and laser relative intensity noise, or RIN) is uniformly distributed over bandwidth. This bandwidth is usually limited by the final component in the system (e.g., by the resolution bandwidth of a spectrum analyzer).

*3. U.S. Navy Contract No. N00164-97-C-0056 (NSCW, Crane, IN).

*4. Air Force Research Laboratory, Rome, NY Contract No. F30602-97-C-0160.

*5. National Institutes of Health (Heart, Lung, and Blood Institute) Grant 2 R44 HL54974-02A1.

6. The spurious-free dynamic range, as limited in this case by third-order non-linearities, is the ratio to the noise level of the level of two equal signals which mix in the system to cause spurs equal to that noise level in a given noise bandwidth. It can be shown to depend on that bandwidth to the 2/3 power. The voltage or current of the spurs is proportional to the cube of the signal levels; the noise is proportional to the square root of the bandwidth; the power is proportional to the square of the voltage or current. (See, for example, G. Gonzalez, *Microwave Transistor Amplifiers*—Prentice-Hall, Englewood Cliffs, NJ, 1984—p. 179 ff.)

*AFRL-IF-RS-TR-1998-54, U.S. Navy Contract No. N00164-97-C-0056, U.S. Navy No. N00421-97-C-1086 and NIH Grant 2 R44 HL54974-02A1 are limited distribution to U.S. Government Agencies Only.

APPENDIX

MISSION RESEARCH CORPORATION
MODEL 97019-1 PROBE SYSTEM
OPERATING MANUAL

CAUTIONS

DANGER: LASER LIGHT.

• The probe system uses high laser power at 1319 nm.
• Be sure the laser is not emitting whenever connecting or disconnecting fibers. NEVER look at the end of a disconnected fiber connector while the laser is emitting.
• THE END OF THE PROBE HEAD CAN EMIT DANGEROUS AMOUNTS OF LASER LIGHT. DO NOT LOOK AT THE END OF THE PROBE HEAD FROM A DISTANCE OF LESS THAN ONE FOOT (30 cm).
• Observe all precautions and follow all instructions in the laser manual.

DANGER: EXPOSED 120-VAC

• The inside of the Probe Interface Box contains exposed 60-cycle, 120-volts AC power. ALWAYS DISCONNECT THE BOX WHEN LEFT OPEN. USE EXTREME CARE WHILE MAKING ADJUSTMENTS INSIDE THE BOX WHILE THE POWER CONNECTED. If service is required, contact MRC. (703 339-6500, Rick Smith, Extension 148.)

DAMAGE HAZARDS

Various parts of the probe system are **EXTREMELY FRAGILE.**

• THE PROBE HEAD IS ESPECIALLY FRAGILE. DO NOT DROP OR OTHERWISE EXPOSE TO MECHANICAL SHOCK. DO NOT REMOVE THE PROTECTIVE FOAM JACKET.
• IF THE PROTECTIVE JACKET IS REMOVED FOR ANY REASON, DO NOT TOUCH THE MODULATOR/ANTENNNA ASSEMBLY OR ALLOW IT TO COME INTO CONTACT WITH ANY OBJECT.
• FIBER CONNECTORS ARE EXTREMELY FRAGILE.
  - DO NOT TOUCH THE CERAMIC FERRULES (white connector ends which protrude into the adapters) OR ALLOW THE VERY ENDS OF THE FERRULES TO COME INTO CONTACT WITH OTHER OBJECTS.
  - DO NOT PUT MECHANICAL STRESS ON THE CONNECTORS, ESPECIALLY THE FERRULES
  - DO NOT OVERTIGHTEN THE CONNECTORS (MINIMUM TORQUE IS SUFFICIENT)
• ALL FIBER ASSEMBLIES IN THE PROBE INTERFACE BOX ARE EXTREMELY FRAGILE. DO NOT TOUCH.

OPERATING INSTRUCTIONS

(1) Refer to Figures A1 and A2 and also to the text of Mission Research Corporation (MRC) Report MRC/WDC-R-439 on Air Force Contract No. F30602-97-C-0044 for probe system illustrations and discussions concerning probe system theory and operation.

Figure A1. Probe Interface Box front panel.

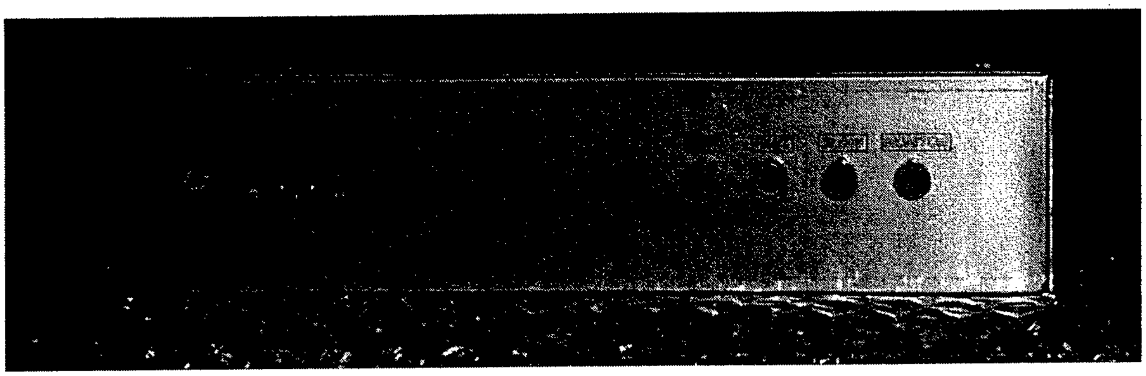

Figure A2. Probe Interface Box rear panel.

(2) Supply a Lightwave Electronics (Mountain View, CA) isolated, fiber coupled, low-noise, high-coherence-length (e.g., > 20 m), high-power (e.g., > 50 mW into the fiber) 1319-nm, for example, the 125-1319-XXX series. An alternative is the free-space (non-fiber-coupled) Lightwave 126-1319-XXX series, which can be fiber coupled using components available from various vendors including Oz Optics of Carp, Ontario, Canada. (This is the option which was used in the work reported in MRC Report MRC/WDC-R-439.) The deliverable probe system includes an OFR Model IO-G-1320 isolator which can be connected between the laser and the Probe Interface Box to supply the required isolation.

NOTE: The laser output fiber pigtail should be a polarization maintaining (PM) fiber cable with FC/APC type connectors for minimum reflections.

NOTE: It is recommended the an optical power meter be used to verify that the laser is operating correctly.

(3) Connect the PM fiber cable from the laser (or the OFR isolator, if used) to the "LASER IN" port on the front panel of the Probe Interface Box.

NOTE: Adapters must be used to connect two fibers together. The keys in the connectors must slide at least part way into the slots in the adapter.

NOTE: Most of the fiber connections require a Wave Optics WA-70 adapter. Some WA-70 adapters are made for different size connector keys than others. Ii is typical for the key to only go part way into the slot. If the connector key will not go into the slot in the adapter at all, try either the other end of the same adapter or else a different WA-70 adapter. If the key is so loose that it allows some rotation of the connector in the adapter, it is recommended, although not strictly necessary, that the other end of the same adapter or else a different WA-70 adapter be tried for a tighter fit. Contact either MRC or else Wave Optics, Inc. of Mountain View, CA (650 967-0700) with questions about adapters or to obtain replacement adapters.

NOTE: The connection inside the Probe Interface Box between the MP Fiberoptics isolator and the Lasertron detector requires a Wave Optics WA-10 type adapter. All other connections require a Wave Optics WA-70 adapter.

NOTE: The fiber connectors and adapters must be kept clean. Clean the ends of the ceramic connector ferrules (white tips of the connectors) with a small drop of acetone (on the ferrule end only) and lint free paper. Use only the stiffness of the paper itself to apply any force to the ferrule. DO NOT SOAK THE CONNECTOR WITH ACETONE, as this may cause the connector to come apart. Clean the inside of the adapters with a dry pipe cleaner.

(4) Connect the probe head PM fiber pigtail to the "PROBE IN" port on the Probe Interface Box via the long PM jumper provided with the probe system.

(4) Connect the "MONITOR" BNC coaxial output port on the rear panel of the Probe Interface Box to a DC coupled oscilloscope (at, e.g., 1V/division).

(5) Supply AC power to the Probe Interface Box and turn the unit "ON." Confirm that the "POWER" indicator LED is lit.

(6) Supply power to the laser, and place in the laser in an emitting state.

(7) Observe rapid fluctuations on the oscilloscope. Note (or mark with cursors) the approximate maximum and minimum values of these fluctuations.

(8) After at least 30 seconds, while leaving the laser in the emitting state, turn the Probe Interface Box off. Remove the lid from the Probe Interface Box. **CAUTION: AVOID EXPOSURE TO THE 120-VAC POWER INSIDE THE PROBE INTERFACE BOX.**

(9) Connect the "FAST" BNC coaxial input output port on the rear panel of the Probe Interface Box to the "FAST" tuning input on the Lightwave Electronics laser power supply.

(10) Turn the Probe Interface Box back on. If the oscilloscope display is a steady, flat line between the fluctuation extremes noted under Step (7), proceed to Step (11).

NOTE THAT IF PARTS OF THE PROBE SYSTEM ARE SUBJECT TO HIGH LEVELS OF HIGH-FREQUENCY VIBRATION, IT MAY NOT BE POSSIBLE TO ACHIEVE A STABLE DISPLAY. THE PROBE SYSTEM CANNOT BE USED IN SUCH CASES.

(10A) If the oscilloscope display is not a steady, flat line at a level between the two extremes noted in step (7), disconnect the cable from the "FAST" input on the laser power supply (coming from the "FAST" output on the Probe Interface Box), and connect it to a DC-coupled oscilloscope. Verify that the fluctuations in this signal vary between approximately ± 3 V. If so, proceed to Step (10B). If not, call MRC, Rick Smith (703 339-6500, Ext. 148.) before proceeding.

(10B) If the "FAST" output voltage is varying between ± 3 V, turn off the Probe Interface Box, reconnect the "FAST" output to the "FAST" tuning input on the laser power supply, and turn the Probe Interface Box back on. Adjust the un-labeled variable resistor (at the top of Figure A3, near the Lasertron detector—*not* variable resistor R5) on the feedback electronics board in the Probe Interface Box to attempt to achieve a flat stable line between the two extremes of the fluctuations noted earlier under Step (7). If this is achieved, proceed to Step (11). If not, call MRC (703 339-6500, Rick Smith, Ext. 148.) before proceeding.

(11) If the oscilloscope display is a steady flat line between the fluctuation extremes noted under Step (7), adjust R52 on the feedback electronics board in the Probe Interface Box as needed to move this line to the approximate mid point between these two extremes.

(12) The probe system is now ready for use. While using the probe system, observe all CAUTIONS listed earlier in this manual. Periodically observe the fluctuations of the monitor output on the DC coupled oscilloscope seen when the "FAST" output (rear panel) is disconnect from the "FAST" input on the laser power supply. After reconnecting, verify that a flat, stable line half way between the fluctuation extremes is seen. Adjust R52 to correct the position of this line as needed. While reconnecting, it is recommended that the Probe Interface Box be turned off.

NOTE: To achieve approximate absolute RF field measurements, it is highly recommended that a calibration with the probe immersed in an accurately-known RF field at the frequencies of interest be performed. Note also that the probe system is also subject to sensitivity (calibration) drifts of 1 dB or more over time and temperature.

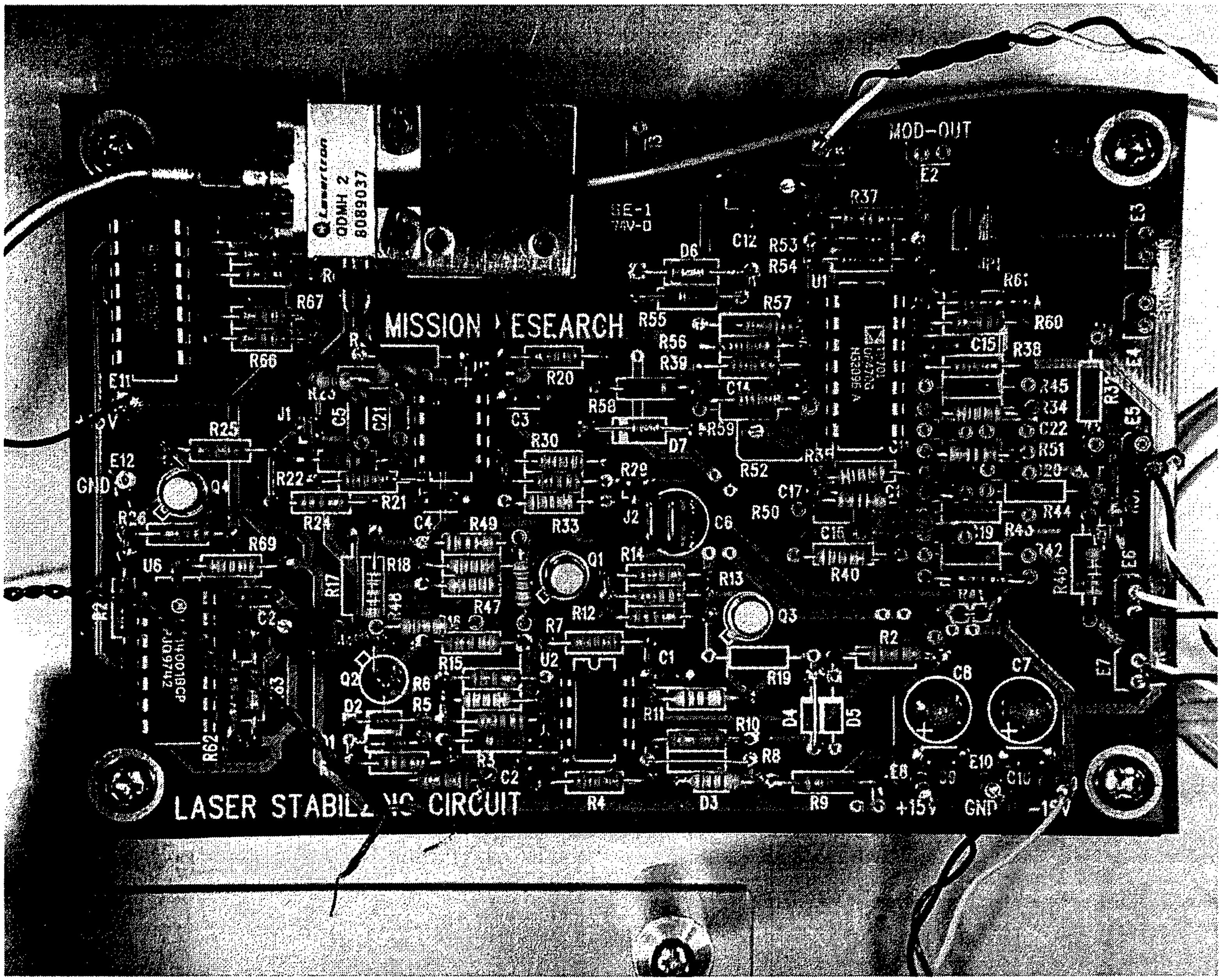

Figure A3. Feedback electronic circuit in Probe Interface Box

MISSION RESEARCH CORPORATION
MODEL 97019-1 PROBE SYSTEM
PARTS LIST

- MRC probe head with protective jacket.
- OFR Model IO-G-1320 PM Isolator (SN 156622).
- Wave Optics PM Splitter (SN 12209)
- Oz Reflector (FORF-13-A=1320-P-BL-SP)
- Lasertron Detector QDMH2-SPEC (SN 8028401)
- MP Fiberoptics Isolator (SN716197)
- Miteq Amplifier: AFS4-00101800-40-ULN
- Cosel YW1015U power supply
- MRC feedback electronics board.
- Long (≥ 18 m), 3-mm-jacketed PM fiber cable with FC/APC connectors.
- 1-ea WA-10 FC adapter from Wave Optics of Mountain View, CA.
- 6-ea WA-70 FC adapters from Wave Optics of Mountain View, CA

Note that the connection inside the Probe Interface Box between the MP Fiberoptics isolator and the Lasertron detector requires a Wave Optics WA-10 type adapter, all others require a type WA-70. When ordering new adapters, be sure to measure the width of the connector keys for which the adapter is intended and convey this information to Wave Optics.

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